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**Initial Results From A Cryogenic Coaxial Injector In An
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Abstract

A coaxial injector was made to inject liquid nitrogen (LN2) with a coflow of gaseous nitrogen (GN2) in its annular region as part of a program to better understand the nature of the interaction between acoustic waves and liquid fuel jets in cryogenic rocket engines. The LN2 was injected into a room temperature high-pressure chamber having optical access on its sides. A piezo-siren capable of generating sound waves with an SPL of up to 180 dB was employed under two chamber pressures of 2.14 and 4.86 MPa. The reduced pressures for these pressures are 0.63 (subcritical), and 1.43 (supercritical), respectively. The assembly consisting of the acoustic driver and the high-pressure chamber form a cavity that resonates at several frequencies, the strongest being at 2700 and 4800 Hz. Initial results for only one LN2 flow rate but at three co-flow rates and at 2700 Hz are reported here. The nature of the aforementioned interactions has been captured via a CCD camera high-speed imaging system. These evidences indicate that the warmer co-flow GN2 affects the thermodynamic condition of the LN2 jet near the inner wall surface, reducing the jet initial visual diameter, particularly at higher co-flow rates. Dramatic effects of the periodic transverse acoustic waves can be seen to impose a sinusoidal shape to the jet appearance. The wavelength of this wavy shaped structure is established by the acoustic-induced transverse deflection of the jet considering the fact that the jet exists in the velocity antinode of the acoustic field. Injector modifications to provide a more realistic flow conditions and collection of more data are needed to fully map and explain these initially-observed interesting interactions.

Introduction

In evaluating injector performance, it is customary to conduct reasonably simple and cost-effective non-fired studies at elevated ambient pressures. Water and nitrogen are often used as simulants under non-fired conditions for reasons of safety and convenience. The question often arises as to what extent the information gained in such cold tests is of value. Normally, the tests are designed to match certain non-dimensional parameters to those of actual combustors, for example, liquid-to-gas mass, momentum, density, and velocity ratios, and Weber, Reynolds, Ohnesorge, etc. numbers. Matching all parameters

is not always possible. Therefore, it is highly desirable to follow a systematic approach whereby links are established between non-fired and fired tests. These established links make the non-fired studies a valuable exercise for design engineers. Non-fired studies can yield valuable insight into the atomization efficiency and performance of different designs of injectors, for instance. The non-fired studies reported in this paper were performed under a similar logic whereby the results will eventually be linked to fired conditions inside cryogenic liquid rocket engines.

In this preliminary work, we report some initial results obtained on a coaxial injector. The key idea is to systematically extend extensive results obtained on single-jet injectors obtained by Chehroudi *et al* [1,2,3] by adding an annular co-flow. In the preliminary results reported here, the center jet is liquid nitrogen and the co-flow is gaseous nitrogen, and the co-flow velocity is small in order to relate the results to previous non-coflowing results. Results are reported at a subcritical pressure and a supercritical pressure. Future efforts will include subcritical and supercritical results at higher co-flow velocities and using helium as the co-flow gas, as well as fired results using liquid oxygen and gaseous hydrogen. In addition, the test facility has a unique high-pressure acoustic driver, also used in a single-jet study of Chehroudi *et al*. [4], where the effects of acoustic perturbation can be studied under both subcritical and supercritical conditions. This should create a unique set of features to approach the problem of combustion instability in cryogenic liquid rocket engines systematically and in a stepwise manner.

Experimental Setup

Cryogenic liquid nitrogen is injected into a room temperature high-pressure chamber with full optical access on its four sides. Figure 1 shows a schematic diagram of the experimental rig. The stainless steel chamber can withstand pressures and temperatures of up to 20 MPa and 473 K, respectively. It has two facing circular sapphire windows for optical diagnostics. Liquid N₂ is used to cool and/or liquefy the injectant passing through the cryogenic cooler prior to injection. The mass flow rate of the injectant is measured and regulated via a mass flow meter and a precision micrometer valve. Back-illumination of the jet is accomplished with diffuse light flashes (0.8 μ s duration). A model K2 Infinity long distance microscope is

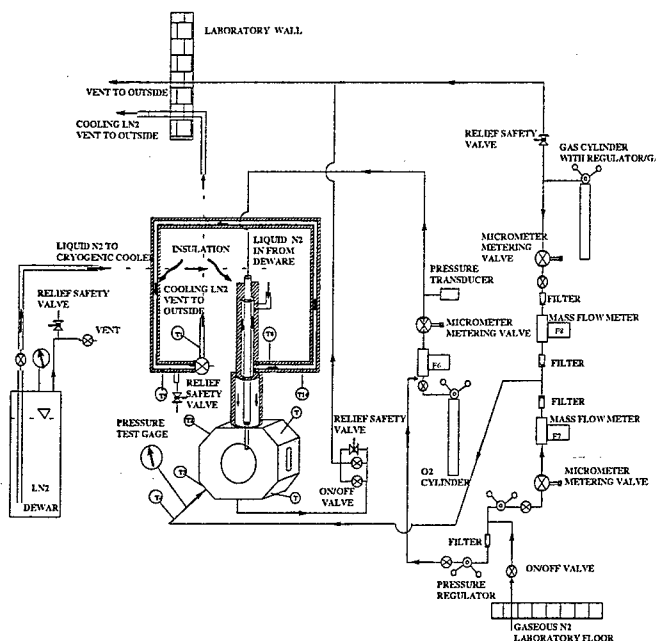


Figure 1. Schematic diagram of experimental setup for sub- to supercritical jet injection

used with a high resolution (1280(H) x 1024(V) pixels in an 8.6(H)x6.9(V) mm actual sensing area with a pixel size of $6.7\mu\text{m} \times 6.7\mu\text{m}$) CCD camera by the Cooke Corporation to form images of the injected jets. For the results reported, the cryogenic jet is injected through a sharp-edged stainless steel tube having a length L of 50 mm, and inner and outer diameters measuring $d_i = 0.508$ mm and $d_o = 1.59$ mm, respectively. The resulting L/d_i was 100, which is sufficient to ensure fully developed turbulent pipe flow at the exit plane. The Reynolds number in these studies ranges from 6,000 to 30,000. The outer annular tube has the inner diameter of 2.286 mm, forming a gaseous fluid annular passage of 0.348 mm in the radial direction. This was the first of a series of designs with different aforementioned dimensions that was tested and initial results are presented here. Figure 3 shows a picture of the assembled coaxial injector used in this study. The gas first goes into a ring manifold to be equally distributed later through four 90-degree spaced holes into the annular region well upstream of the injector exit plane. The rig is fully instrumented to measure pressure, temperature, and mass flow rate of the injected fluid. A specially designed piezo-siren by Hersh Acoustical Engineering, Inc., capable of producing sound pressure levels (SPL) of up to 180 dB (in an impedance tube) at its resonant frequencies (lying between 1000 to 8000 Hz) and at pressures up to 2000 psi is used with a circular-to-rectangular transition coupling to bring the acoustic waves into the interaction zone inside the chamber. A model 601B1 Kistler piezoelectric-type pressure transducer is used to measure the acoustic pressure variations inside the chamber at various pressures very near the jet location. The piezo-siren acoustic driver is able to generate between 161 to 171 db when coupled with the high-pressure chamber. The siren hardware is illustrated in Figure 2.

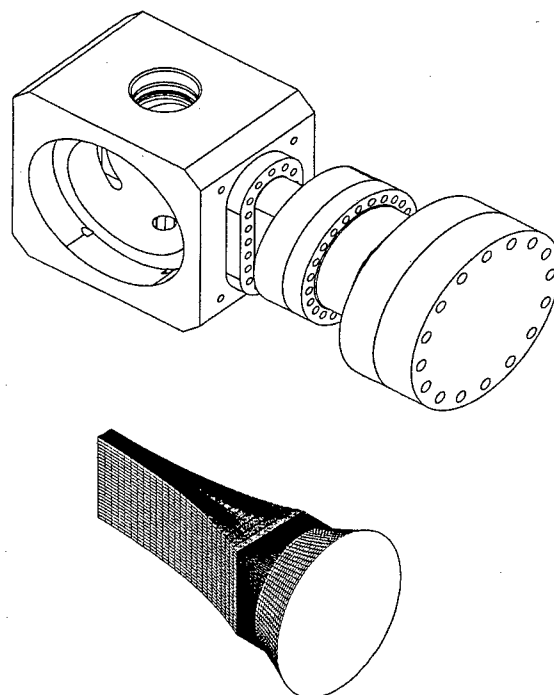


Figure 2. Top: coupling of the acoustic driver (piezo-siren) with the high-pressure chamber. Bottom: the design of the circular-to-rectangular channel to guide the waves into the chamber.

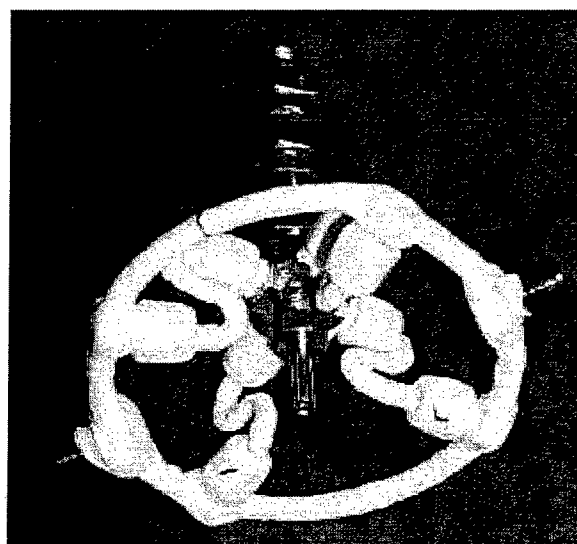


Figure 3. A picture of the assembled coaxial injector.

Previous Results at AFRL on Supercritical Jets

During the past three years, results from the injection of several fluids into an ambient under both sub- and supercritical pressures at sufficiently high Reynolds numbers to be considered as fully-turbulent flow have been reported for the same test facility shown in Fig.1, see *Chehroudi et al. [1,2,3]*. A variety of ambient fluids was used into which pure N_2 , He, and O_2 fluids were injected. The ef-

fects of chamber pressure (density) ranging from the thermodynamic subcritical to supercritical values at a supercritical chamber temperature (based on the critical pressure and temperature, P_c , T_c , of the injectant) were observed by the acquisition of shadowgraph images from the injector exit region using a CCD camera illuminated by short-duration light pulses.

At sufficiently low subcritical chamber pressures, the disturbances on the jet interface amplified downstream and eventually broke up into irregularly-shaped small entities. A further increase of chamber pressure initiated the formation of many small ligaments and droplets at the interface of the jet only within a narrow regime below the thermodynamic critical pressure of the injected pure fluid, resembling a second wind-induced liquid jet breakup. At even higher chamber pressures, near but below the critical pressure of the injectant, the expected transition into a full atomization regime to produce a liquid spray was inhibited due to reduction of both the surface tension and the heat of vaporization. The jet appearance changed abruptly at this pressure and resembled that of a turbulent gas jet for all higher chamber pressures. The initial growth rate of the jet was plotted together with available data on liquid fuel injection in diesel engine environments, and turbulent incompressible, supersonic, and variable-density jets and mixing layers. The resulting plot is unique in its own right, covering four orders of magnitude in density ratio. At near- and super-critical pressures, these measurements agreed well with the theoretical growth rate equations proposed by Brown [5], Papamoschou and Roshko [6], and Dimotakis [7] for incompressible but variable-density turbulent mixing layers. This constituted the first quantitative evidence in support of the past qualitative observations that the jet appeared to evolve into a gas-like behavior under supercritical condition. The geometry of the jet interface was also examined for the first time by fractal analysis. The results clearly indicated a transition from a Euclidean to a fractal interface, with a fractal dimension close to values measured for gaseous turbulent jets. This provided an additional quantitative evidence for the hypothesis that the jet evolved into a gas-like behavior. An equation was proposed based on a physical model proposing that at the point of transition from liquid-like to gas-like appearances and growth rates, the characteristic time of the vaporization process is of the same order as that of the interfacial "bulge" formation/separation events. The model equation agreed well with the experimental growth rate data. The initial growth rate of the jet as judged by the Raman signature was in reasonably good agreement with our earlier measurements using shadowgraphy if twice the FWHM of the normalized intensity plots were used, see Chehroudi *et al.* [8]. The interaction of the acoustic waves with the same jet studied earlier was considered in Chehroudi *et al.* [4]. It was found that the impact of the acoustic waves on the jet structure was strongest from low to particularly near-critical chamber pressures and at low injectant flow rates. No significant effects of the acoustic waves were detected at the supercritical chamber pressure examined under the

range of the excitation Strouhal (St) number studied (0.03 to 2).

Experimental Results

In this paper, only preliminary results from a newly designed coaxial injector are shown. Currently, the system is not fully optimized and the work is in progress. Hence, the purpose here is to demonstrate opportunities for systematic acoustic-coaxial jet interaction studies with the intention to elucidate some features of combustion instabilities in cryogenic liquid rocket engines.

Figure 4 shows images taken at a subcritical chamber pressure of 2.14 MPa (a reduced pressure of .63) at three different coflow mass flow rates, exposed to no acoustic field (off) and to a high acoustic field (on) at a frequency of 2700 Hz. Figure 4 (a) is the base or reference image with the lowest value of the co-flow (nearly zero) and for when the acoustic excitation is turned off. First, the effects of the co-flow can be observed by inspection of Figs. 4 (a), (c), and (e). Although the velocity of the co-flow is not as high as it is desired to enable sufficiently strong aerodynamic interaction, one can observe a reduction of the jet diameter even at the injector exit plane. Also, one sees a simultaneous fuzziness of the jet boundary covered with a cushion layer of vaporized (lower density) and cold nitrogen. This cushion feature can be better seen in high resolution images. The aforementioned co-flow velocity limitation is being relaxed by modifications of the injector outer tube dimensions and will be examined in the near future. Currently, co-flow/jet velocity ratios in the range of about 1 to 3 are achievable. The nitrogen co-flow gas temperature (~ 250 K) is not low enough to be detected in our images but is sufficiently warm to affect the near-wall liquid nitrogen thermodynamic states inside the inner tube which guides the LN₂ jet. The reduction of the visual jet diameter at the exit plane as the co-flow is raised from 5 mg/s to 188 mg/s is thought to be due to this effect. No substantial further differences are seen when the co-flow rate is further raised to 350 mg/s in Fig. 4 (e).

The effects of the transverse external acoustic waves at 2700 Hz at a subcritical chamber pressure and at three different co-flow rates can be seen by examining the following image pairs: Figs. 4 [(a) and (b)], [(c) and (d)], and [(e) and (f)]. The acoustic waves oscillate between left and right in these figures as well as in Fig. 5. Earlier pressure field mapping using a pressure transducer showed that the jet is located at a velocity antinode at this frequency. A velocity antinode means large transverse velocity oscillations. The impact of the acoustic waves is seen to accelerate the jet instability and breakup processes. A distinct sinusoidal spatial wave has been imposed on the jet in Figs. 4 (d) and 4 (f). It is possible that the sinusoidal appearance is actually the result of a helical structure, but this has not yet been confirmed. From estimates of the co-flow gas velocity, the wavelengths seen in the figures are consistent with the driving frequency of 2700 Hz.

At a supercritical chamber pressure of 4.86 MPa (a reduced pressure of 1.42), an increase in the co-flow rate alone tends to slightly narrow the jet with no other distinct visual effects. This unexpected result is due to the limitation of the co-flow velocity mentioned earlier. However, the effects of the acoustic waves are not only to increase the initial jet angle, but to again impose a sinusoidal shape to the jet, see Figs. 5 (b), (d), and (f). The wavelength is noticeably and consistently smaller than what is seen under the subcritical chamber pressure, see Figs. 4 (d) and (f). One would then expect that as the penetration rate of the newly injected fluid is reduced, for example under higher chamber pressures (supercritical), the wavelength should decrease. This is indeed what one sees examining Figs 4 and 5. Rough calculation of the jet velocity from the acoustic frequency and this spatial wavelength gives velocities near the jet velocity estimated from the knowledge of mass flow rates. Depending on the relative magnitude of the jet exit momentum to that imposed by the acoustic waves and frequencies, one may or may not expect to see these spatial waves. Also, note that the onset of this wavy feature moves closer to the injector at the supercritical condition. In summary, the effects seen in Figs. 4 and 5 are the combined effects of the coflow and acoustic perturbations. More data is needed to fully map these interactions.

Summary and Conclusions

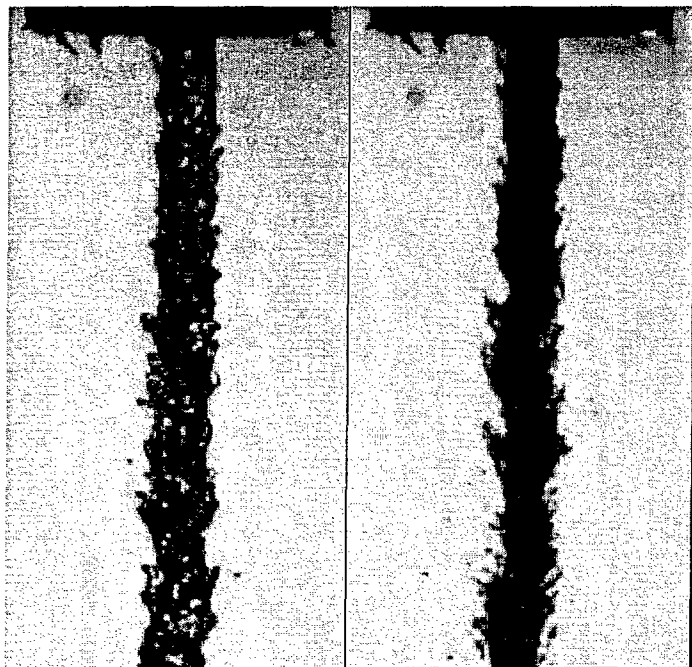
Initial results from a coaxial injector, injecting liquid nitrogen surrounded by a gaseous nitrogen co-flow into a subcritical and supercritical ambient with and without acoustic excitation showed a large impact of the acoustic waves on the jet structure. In essence, the acoustic waves tend to impose a sinusoidal shape on the jet with a wavelength that can be explained through periodic transverse variations of the chamber gas velocities at the velocity antinode of the acoustic field. Evidence indicates that there is strong heat transfer interaction inside the injector between the co-flow gaseous nitrogen and the liquid nitrogen jet. Due to the low GN2 coflow velocities achieved thus far, dominant aerodynamic interaction was not observed. Injector modifications are underway to provide a more realistic flow conditions and more data is needed to fully map the aforementioned interactions.

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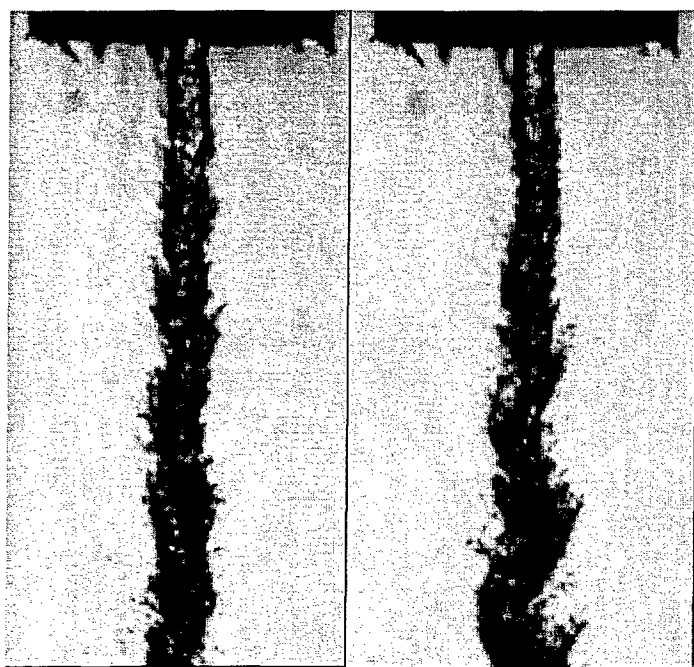
(a) 300-305-5-off

(b) 300-305-5-on



(c) 300-305-188-off

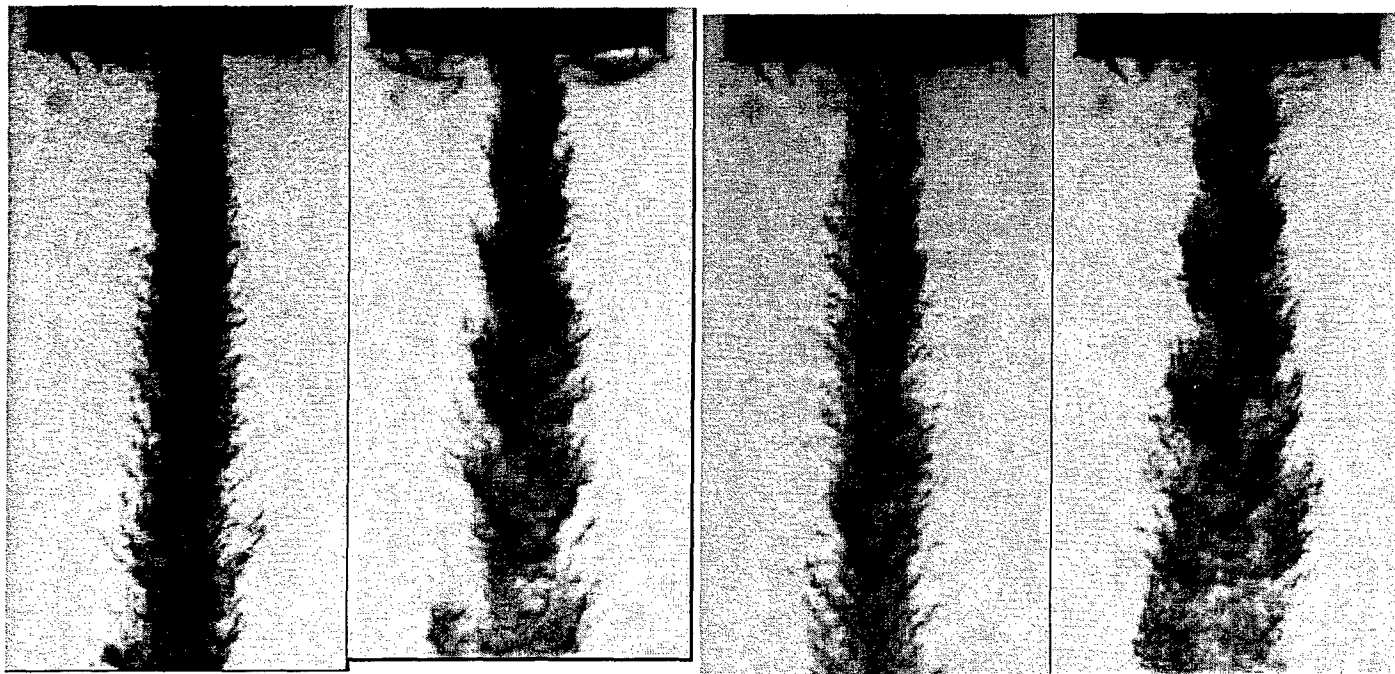
(d) 300-305-188-on



(e) 300-305-350-off

(f) 300-305-350-on

Figure 4. Shows effects of acoustic waves on a coaxial injector at a subcritical pressure and at three different co-flow mass flow rates of 5, 188, 350 mg/s. The code, 300-305-5-off means a chamber pressure of 2.14 MPa (300 psig), a jet flow rate of 305 mg/s, and a co-flow rate of 5 mg/s, with acoustic excitation turned off. Acoustic field frequency is 2700 Hz when on.

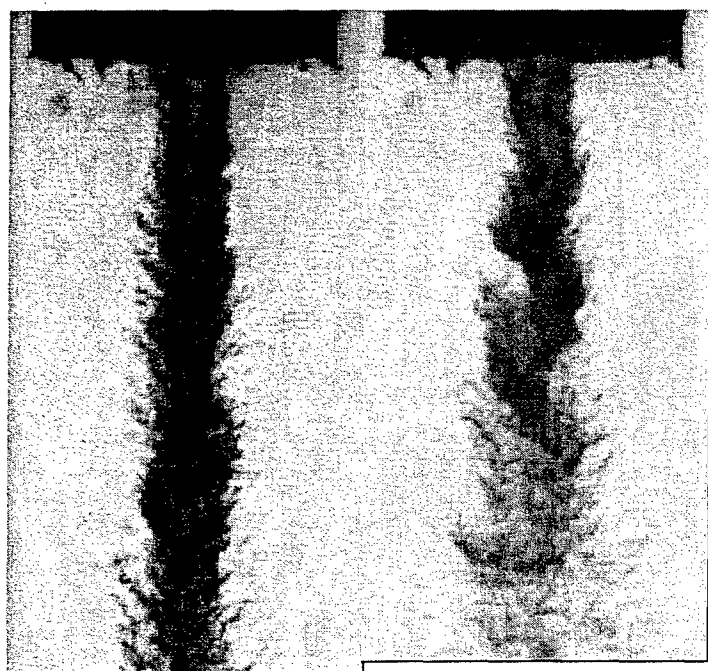


(a) 700-305-5-off

(b) 700-305-5-on

(c) 700-305-188-off

(d) 700-305-188-on



(e) 700-305-350-off

(f) 700-305-350-on

Figure 5. Shows effects of acoustic waves on a coaxial injector at a supercritical pressure and at three different coflow mass flow rates of 5, 188, 350 mg/s. The code, 700-305-5-off means a chamber pressure of 4.86 MPa (700 psig), a jet flow rate of 305 mg/s, and a co-flow rate of 5 mg/s, with acoustic excitation turned off. Acoustic field frequency is 2700 Hz when on.